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The Effects of Aerodynamic Jump Caused by a Uniform Sequence of Lateral Impulses

by Gene R. Cooper

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14. ABSTRACT The linear theory for spinning projectiles is extended to account for the application of a uniform sequence of lateral square impulses activated during free flight. Analytical results are shown to produce simple contributions to the familiar aerodynamic jump formulation for a single impulse. Inquiries regarding modifications of jump smearing are addressed, and comparative calculations are presented. The formulation shows that an additional jump phase angle and the jump magnitude are changed by a multiplying factor describing the impulse sequence.			
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1. Introduction

This report extends the papers by Cooper (*1*) and Cooper and Costello (*2*) which examined the aerodynamic jump characteristics of a spinning projectile subjected to a single lateral impulse. The extension considers a sequence of lateral impulses, each separated by a constant arc length T. Jump effects attributable to gravity have now been included since experience has shown that when one ignores gravity, as is usually done, it may lead to incorrect results (*3*). The modification parallels the analysis of Cooper (*1*) and Cooper and Costello (*2*) where the changes in the analysis stem from the impulse sequence driving terms and a corrected limiting procedure that retains the pertinent gravity terms influencing aerodynamic jump.

2. Projectile Dynamic Model

The analysis here follows the same analysis presented in Cooper and Costello, and the equations of motion continue to have the following form for the linear theory (see figures 1 and 2):

$$\left\{ \begin{array}{c} \widetilde{u} \\ \widetilde{v} \\ \widetilde{w} \end{array} \right\} = \left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & coa\phi \end{array} \right\} \left\{ \begin{array}{c} u \\ v \\ w \end{array} \right\} \tag{1}$$

$$x' = D \tag{2}$$

$$y' = \frac{D}{V}\widetilde{v} + D\psi \tag{3}$$

$$z' = \frac{D}{V}\widetilde{w} - D\theta \tag{4}$$

$$\phi' = \frac{D}{V}p \tag{5}$$

$$\theta' = \frac{D}{V}\widetilde{q} \tag{6}$$

$$\psi' = \frac{D}{V}\widetilde{r} \tag{7}$$

$$V' = \frac{\rho SDC_{XO}}{2m}V - G\theta \tag{8}$$

1

$$p' = \frac{\rho S D^2 C_{LDD}}{2 I_X} V + \frac{\rho S D^3 C_{LP}}{4 I_X} p \qquad (9)$$

$$\begin{Bmatrix} \tilde{v}' \\ \tilde{w}' \\ \tilde{q}' \\ \tilde{r}' \end{Bmatrix} = \begin{bmatrix} -A & 0 & 0 & -D \\ 0 & -A & D & 0 \\ B/D & C/D & E & -F \\ -C/D & B/D & F & E \end{bmatrix} \begin{Bmatrix} \tilde{v} \\ \tilde{w} \\ \tilde{q} \\ \tilde{r} \end{Bmatrix} + \begin{Bmatrix} Y_I \\ Z_I + G \\ M_I \\ N_I \end{Bmatrix} \qquad (10)$$

$$\begin{Bmatrix} A \\ B \\ C \\ E \\ F \end{Bmatrix} = \begin{Bmatrix} \dfrac{\pi \rho D^3 C_{NA}}{8m} \\[2ex] \dfrac{\pi \rho p D^5 C_{YPA}\, SLCOM}{16 I_y V_0} \\[2ex] \dfrac{\pi \rho D^4 C_{NA}}{8 I_y} \\[2ex] \dfrac{\pi \rho D^5 C_{MQ}}{16 I_y} \\[2ex] \dfrac{p D I_x}{I_y V_0^2} \end{Bmatrix} \qquad (11)$$

Following the usual linear assumptions, the forward velocity and projectile roll rate are taken to be constant (4), i.e., $V \approx V_0$, $p \approx p_0$.

---

3. Pulse Force and Moment Conditions

The pulse forces applied to the projectile are taken to be lateral impulsive forces and each force is attributable to an actuator attached to the projectile body (see the source terms of equation 10). For this investigation, the force actuators are modeled as a sequence of scaled square wave pulses of length L_n and actuated at $s_n + jT$, making the resulting force and moment components in the non-rolling frame

$$Y_I = \frac{F^* V_0 \sum\limits_{j=0}^{Km} [\text{sgn}(s - s_n - jT) - \text{sgn}(s - s_n - L_n - jT)] \cos\left(\dfrac{Dp}{V_0} s + \varphi_B\right)}{2 L_n} \qquad (12)$$

$$Z_I = \frac{F^* V_0 \sum\limits_{j=0}^{Km} [\text{sgn}(s - s_n - jT) - \text{sgn}(s - s_n - L_n - jT)] \sin\left(\dfrac{Dp}{V_0} s + \phi_B\right)}{2 L_n} \qquad (13)$$

$$M_I = -\frac{M^* V_0 \sum_{j=0}^{Km}\left[sgn(s-s_n-JT)-sgn(s-s_n-L_n-jT)\right]\sin\left(\frac{Dp}{V_0}s+\phi_B\right)}{2DL_n} \tag{14}$$

$$N_I = \frac{M^* V_0 \sum_{j=0}^{Km}\left[sgn(s-s_n-JT)-sgn(s-s_n-L_n-jT)\right]\cos\left(\frac{Dp}{V_0}s+\phi_B\right)}{2DL_n} \tag{15}$$

$$F^* = \frac{DF_d}{mV_0^2} \tag{16}$$

$$M^* = \frac{D^2 F_d X_r}{I_y V_0^2} \tag{17}$$

Note that the last expressions are equivalent to delta function impulses in the limit of $L_n \to 0$.

Swerving motion is measured along the earth-fixed $\mathbf{J_I}$ and $\mathbf{K_I}$ axes. To an observer standing behind the gun tube, these axes are oriented so that positive $\mathbf{J_I}$ is to the right and positive $\mathbf{K_I}$ is pointed downward. The swerving motion results from a combination of the normal aerodynamic forces, as the projectile pitches and yaws, plus the forces and moments attributable to the applied impulses. Swerving motion is thus described by the following equations (*1,2,4*):

$$\frac{y''}{D} = \frac{F_I \cos(Ps+\phi_B)\sum_{j=0}^{Km}\left[sgn(s-s_n-jT)-sgn(s-s_n-L_n-jT)\right]}{2L_n} - \frac{A\tilde{v}}{V_0} \tag{18}$$

$$\frac{z''}{D} = \frac{F_I \sin(Ps+\phi_B)\sum_{j=0}^{Km}\left[sgn(s-s_n-jT)-sgn(s-s_n-L_n-jT)\right]}{2L_n} + \frac{G-A\tilde{w}}{V_0} \tag{19}$$

For a stable projectile, the swerve caused by epicyclical vibration decays as the projectile progresses down range and does not affect the long-term lateral motion of the projectile. Long-term center of mass solution, or swerve, contains terms that remain bound with arc length s plus terms that are linear with s, and if the total gravity contribution is included, the solution will have higher order diverging terms. These higher order terms are typically denoted as gravity drop and are generally ignored since they are well understood. The linear terms are called aerodynamic jump, caused by initial conditions at the gun muzzle, lateral pulse forces, and aerodynamic characteristics. Setting the diverging gravity terms to zero and subsequently evaluating the following limits formally define aerodynamic jump

$$\lim_{s\to\infty}\frac{y(s)}{Ds}=\Gamma_J \qquad \lim_{s\to\infty}\frac{z(s)}{Ds}=\Gamma_K \tag{20}$$

3

When a lateral pulse is applied to the projectile at arc length s_n, its effect on the target impact point is predominantly attributable to aerodynamic jump because damping rates and target distance are sufficient to allow the epicyclical transients to decay. As shown in equation 21, each of the two components of aerodynamic jump is expressed with terms attributable to muzzle conditions and linear gravity effects, plus a term attributable to the uniform sequence of lateral pulse forces and moments:

$$
\begin{Bmatrix} \Gamma_J \\ \Gamma_K \end{Bmatrix} = - \frac{A}{\left[(AF+B)^2 + (AE+C)^2\right]V_0} \begin{bmatrix} AF+B & -AE-C \\ AE+C & AF+B \end{bmatrix} \begin{Bmatrix} v_0 F + w_0 E - q_0 D \\ w_0 F - v_0 E - r_0 D \end{Bmatrix} -
$$
$$
\frac{AG}{\left[(AF+B)^2 + (AE+C)^2\right]^2 V_0} \begin{bmatrix} (AF+B)^2 - (AE+C)^2 & -2(AE+C)(AF+B) \\ 2(AE+C)(AF+B) & (AF+B)^2 - (AE+C)^2 \end{bmatrix} \begin{Bmatrix} 2EF+B \\ F^2 - E^2 - C \end{Bmatrix} + \qquad (21)
$$
$$
\Lambda \begin{Bmatrix} \cos \Pi \\ -\sin \Pi \end{Bmatrix}
$$

in which

$$
Y = \frac{(AF+B)(A(X_r - 3C) - 4C) + (AE+C)(3AF+4B)}{(AF+B)^2 + (AE+C)^2}
$$
$$
Z = \frac{(AF+C)(A(X_r - 3C) - 4C) - (AE+B)(3AF+4B)}{(AF+B)^2 + (AE+C)^2}
$$
$$
\Pi = \frac{P(L_n + KmT)}{2} + P s_n + \phi_B \ - \tan^{-1}(\Sigma_K / \Sigma_J) \qquad (22)
$$
$$
\Lambda = \sqrt{Y^2 + Z^2} \ \frac{FF \sin\left(\dfrac{PL_n}{2}\right) \sin\left(\dfrac{P(Km+1)T}{2}\right)}{(PL_n/2)\sin\left(\dfrac{PT}{2}\right)}
$$

The magnitude, Λ, and phase angle, $\tan^{-1}(\Gamma_K / \Gamma_J)$, of the jump component are calculated from equation 22.
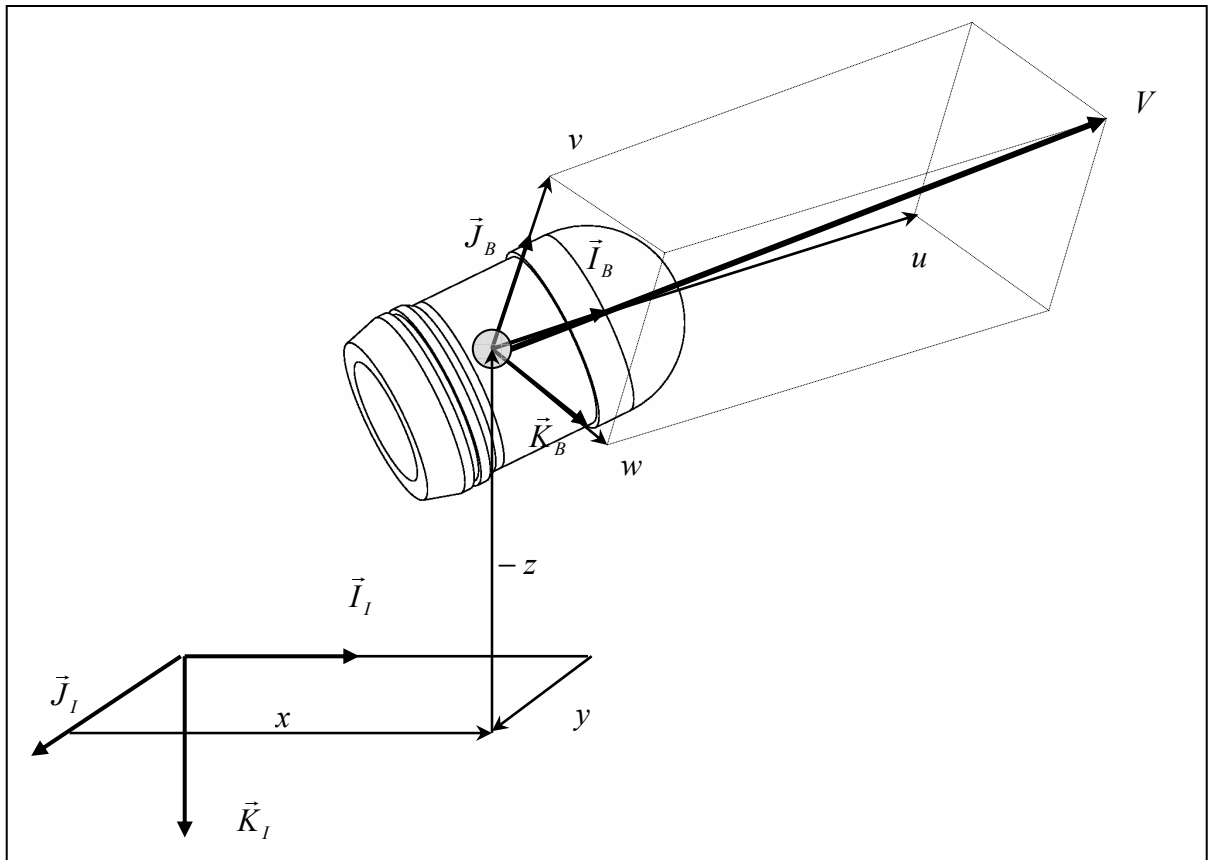
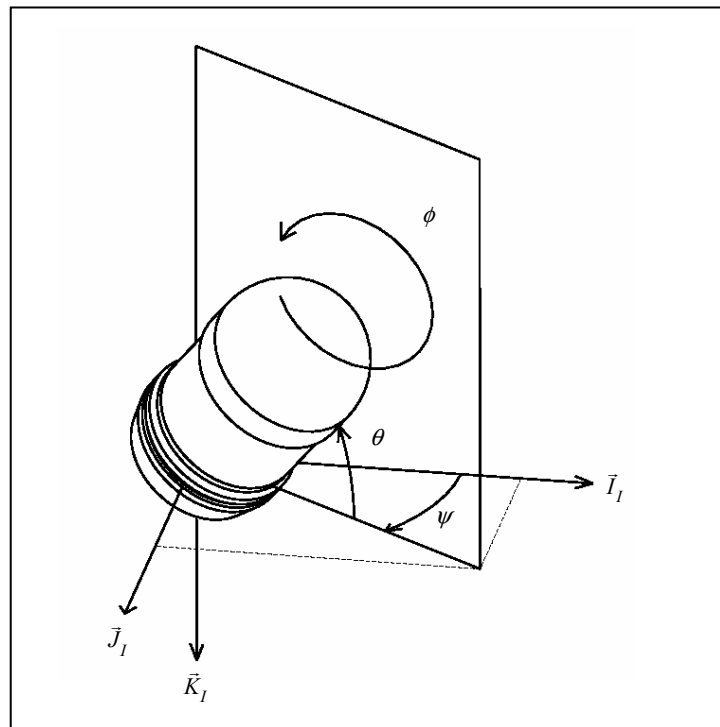Figure 1. Projectile position coordinate definition.

Figure 2. Projectile orientation definition.

4. Changes Caused by a Sequence of Lateral Pulses

To examine the swerve response resulting from a sequence of lateral pulses, it is helpful to write the last term in equation 21 in complex form

$$\Lambda\left(\cos\Pi - i\sin\Pi\right) = \frac{i\,e^{i\Delta}\sin\left(\frac{P\,L_n}{2}\right)\left(A\,MM - (C+iB)FF\right)\sin\left(\frac{P\,T(K_m+1)}{2}\right)}{\left(P\,L_n/2\right)\left(A\,F - iC + B\right)\sin\left(\frac{P\,T}{2}\right)} \tag{23}$$

$$\Delta = \frac{P\left(L_n + KmT\right)}{2} + P\,s_n + \phi_B$$

The last expression shows that the jump attributable to $K_m + 1$ impulses is simply the result of a single impulse multiplied by

$$\Re = \frac{e^{\,i\frac{P\,KmT}{2}}\sin\left(\frac{P\,T(K_m+1)}{2}\right)}{\sin\left(\frac{P\,T}{2}\right)} \tag{24}$$

The most important features of equally spaced multiple impulses are found by examination of the last equation for various values of T and K_m. To emphasize the smearing effects, the roll position, ϕ_N, of the lateral impulse force is assumed to act primarily along the non-rolling Y-axis. This means the arc length, s_N, corresponding to the center of the pulse satisfies the expression $\phi_N = \phi's_N + \phi_B = 2\pi N, N = 0,1,2\cdots$. To assure that this force is acting nominally along the non-rolling Y-axis, the activation point begins at $s_n = s_N - L_n/2$ so that the duration of the impulse brackets $\phi_N = 2\pi N$.

Assuming that all multiple impulses bracket $\phi_N = 2\pi N$ means that the separation arc length must be $T = 2\pi N/P$, and an inspection of equation 24 shows $\Re = K_m + 1$. This makes physical sense because repeated impulses in the same direction should result in a jump that is $K_m + 1$ times the jump for a single impulse. Considering cases when successive impulses are activated at $\phi_N = 2\pi N + \text{integer}\,\pi$ implies that one way to do this is to let $T = \pi(2N+1)/P$. Equation 24 leads directly to

$$\Re = e^{\,i\frac{\pi K_m}{2}}\cos\left(\frac{\pi K_m}{2}\right) \text{ or } \Re = \begin{cases} 1 \to K_m \text{ even} \\ 0 \to K_m \text{ odd} \end{cases},$$

which also confirms physical reasoning.

Plots comparing the effect of smearing between a one- and a two-impulse sequence, $Km = 0,1$ are given in figures 3 and 4 for the applied force $F^* = 3.836\times10^{-5}$ and moment arm

$X_r/D = -0.635$ (see appendix A). These parameters correspond to the case in Cooper's (*1,2*) report for which the jump resulting from a single impulse was greatest. Negative values of X_r indicate that the application point of the pulse force is aft of the mass center. The chosen value

$$T = \frac{3\pi}{2P}$$

shows that a sequence of impulses can cause considerable changes in both Γ_j and Γ_k and these in turn impact the phase angle $\tan^{-1}(\Gamma_K/\Gamma_J)$ because of the pre-multiplier $e^{\frac{iPK_mT}{2}}$ in equation 24. Changes in the phase angle response are readily seen so that the phase angle from a single impulse is shifted by $\frac{PK_mT}{2}$ for K_m additional impulses. In this example, i.e., $T = \frac{3\pi}{2P}, K_m = 2$, the phase is shifted by $\frac{3\pi}{2}$ or increased by 270 degrees.
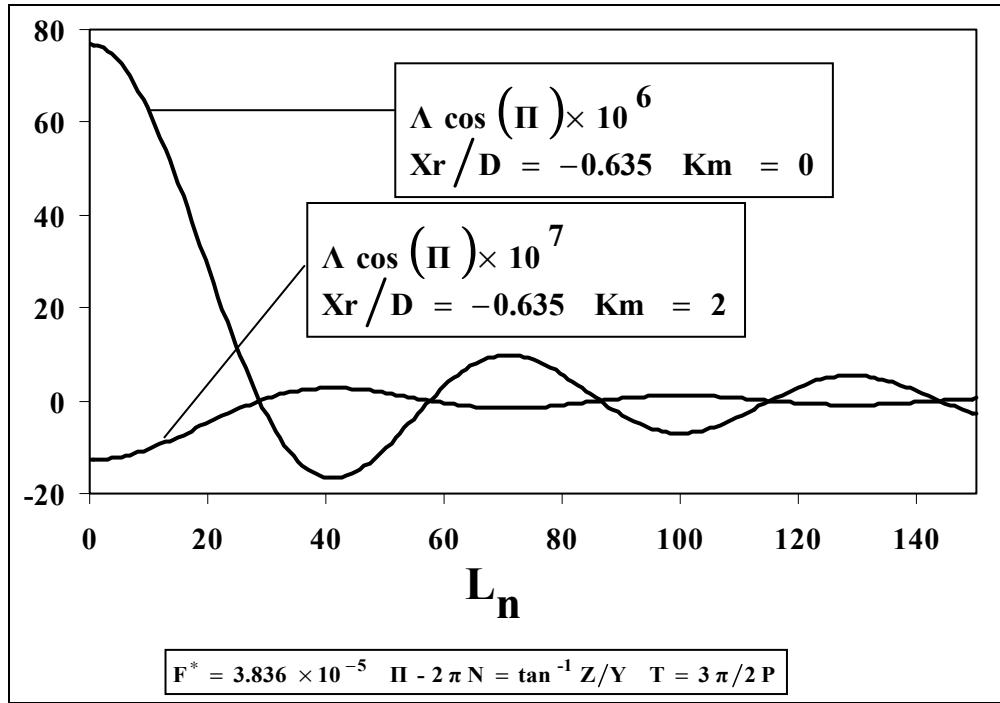

Figure 3. Jump component-J because of lateral impulse versus impulse duration.
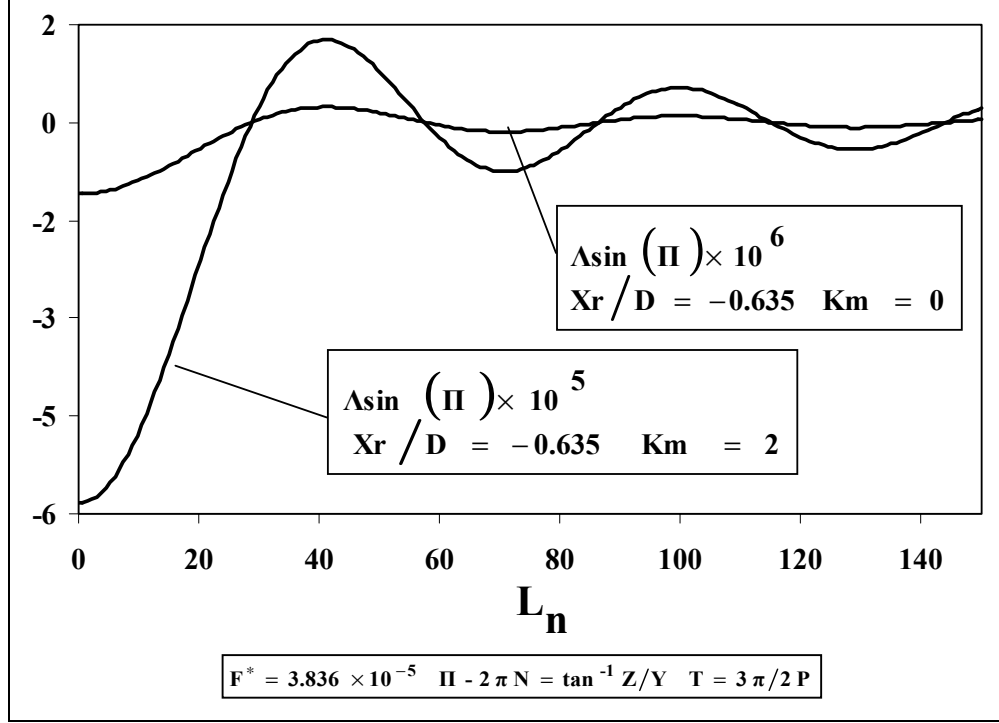
Figure 4. Jump component-K because of lateral impulse versus impulse duration.

Figure 5 gives a chart showing the respective magnitudes, $|\Lambda|$, of the two sample cases given here. These clearly show that repeated impulses that do not bracket $\phi_N = 2\pi N$ can greatly impact the direction of jump induced by lateral impulses. In any case, the magnitude has changed by the factor

$$\frac{\sin\left(\frac{P\,T\,(K_m+1)}{2}\right)}{\sin\left(\frac{P\,T}{2}\right)}\,.$$

Increasing pulse length, L_n, causes the jump components to cyclically decay while the value of L_n at $L_n = 0$ corresponds to a lateral impulse that is proportional to the delta function $\delta(s - s_n)$. Values of L_n where the jump is zero represent situations when the duration of the lateral pulse coincides with a roll cycle. Notice for the case presented that the response attributable to a two-sequence pulse has a predominant direction that depends on the particular choices of T and sequence length K_m.

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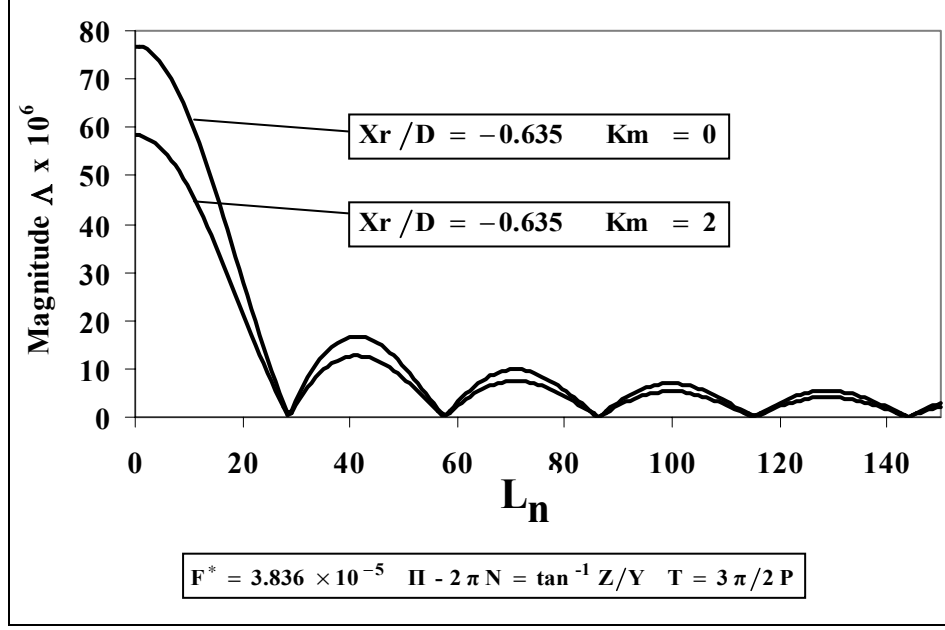
Figure 5. Jump magnitude because of lateral impulse versus impulse duration.

5. Conclusions

The analytical approach for quantifying the effect of a uniform sequence of lateral square impulses disturbing a projectile during free flight is presented. All the analysis was based on projectile linear theory, which produces simple closed form solutions for the assumed square pulse disturbances. The swerving motion caused by a single impulse (*1*) is modified by a multiplying factor, equation 24, which accounts for a uniform sequence, length $K_m + 1$, of impulses. Changes in aerodynamic jump caused by a sequence of lateral impulse forces are shown to produce easy-to-understand additive contributions to the usual aerodynamic jump. Magnitude and phase angle changes that depend on the sequence length and spacing are readily obtained, which may prove useful guidance, navigation, and control.

6. References

1. Cooper, G. R. *Projectile Aerodynamic Jump Due to Lateral Impulsives*; ARL-TR-3087; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003.

2. Cooper, G. R.; Costello, M. Flight Dynamic Response of Spinning Projectiles to Lateral Impulsive Loads; to be published, Sept. 2004 DS-03-1056, *Journal of Dynamic Systems, Measurement and Control*, American Society of Mechanical Engineers.

3. Plostins, P. U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, private communication.

4. Murphy, C. H. *Free Flight Motion of Symmetric Missiles*; BRL Report No. 1216; U.S. Army Ballistic Research Laboratory: Aberdeen Proving Ground, MD, 1963.

Appendix A. Flight Coefficients for a 40-mm Projectile

The numerical values used for the graphical presentations given in this report are shown in the following matrices:

Aerodynamic coefficients:

$$
\mapsto \begin{Bmatrix} C_{X0} \\ C_{X2} \\ C_{NA} \\ C_{YPA} \\ C_{LP} \\ C_{MQ} \end{Bmatrix} = \begin{Bmatrix} 0.279 \\ 2.672 \\ 2.329 \\ -0.295 \\ -0.042 \\ -1.800 \end{Bmatrix} . \tag{A-1}
$$

Physical parameters:

$$
\mapsto \begin{Bmatrix} m \\ I_X \\ I_Y \\ D \\ SL_{COP} \\ SL_{MAG} \\ SL_{CG} \end{Bmatrix} = \begin{Bmatrix} 0.0116\,\text{Slug} \\ 2.85 \times 10^{-5}\,\text{Slug\,ft.}^2 \\ 2.72 \times 10^{-5}\,\text{Slug\,ft.}^2 \\ 0.137\,\text{ft.} \\ 0.237\,\text{ft.} \\ 0.239\,\text{ft.} \\ 0.0713\,\text{ft.} \end{Bmatrix} . \tag{A-2}
$$

Flight characteristics:

$$
\mapsto \begin{Bmatrix} \rho \\ V_0 \\ p \end{Bmatrix} = \begin{Bmatrix} 2.38 \times 10^{-3}\,\text{Slug\,ft.}^{-3} \\ 250.0\,\text{ft. sec.}^{-1} \\ 399.7\,\text{sec.}^{-1} \end{Bmatrix} . \tag{A-3}
$$

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Symbols

C_i Projectile aerodynamic coefficients

D Projectile characteristic length (diameter)

F_d Dimensional impulse force

F^* Non-Dimensional impulse force $F^* = DF_d / mV_0^2$

g Gravitational constant

G Scaled gravitational constant $G = gD/V_0$

I_X
I_Y Mass moments of inertia

L
$\tilde{M}$ Applied moments about projectile mass center expressed in the no-roll frame
$\tilde{N}$

m Projectile mass

P Non-dimensional spin rate $P = Dp/V_0$

p
$\tilde{q}$ Angular velocity components vector of projectile in the no-roll frame
$\tilde{r}$

S Surface area $S = \pi D^2 / 4$

u
v Mass center velocity components in the body reference frame
w

V_0 Forward velocity of projectile

u
$\tilde{v}$ Mass center velocity components in the no-roll reference frame
$\tilde{w}$

X_r Dimensional moment arm length

Y_I
Z_I Applied force components in the no-roll reference frame

$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix}$ Position vector of body center of mass in an inertial reference frame

α		Longitudinal aerodynamic angle of attack
β		Lateral aerodynamic angle of attack
Γ_J	J	Components of aerodynamic jump
Γ_K	K	
Π		Phase angle of the aerodynamic jump caused by a lateral impulse
Σ		Magnitude of jump caused by a lateral impulse
φ		
θ		Euler roll, pitch and yaw angles of the projectile
ψ		
ϕ_B		Euler roll angle of the applied impulse

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       A W HORST JR
    BLDG 4600

1   DIR USARL
    ATTN AMSRD ARL WM BA   D LYON
    BLDG 4600

2   DIR USARL
    ATTN AMSRD ARL WM BC P PLOSTINS
       J SAHU
    BLDG 390

1   DIR USARL
    ATTN AMSRD ARL CI H C NIETUBICZ
    BLDG 328

1   DIR USARL
    ATTN AMSRD ARL CI HC R NOAK
    BLDG 394

3   CDR US ARMY ARDEC
    FIRING TABLES BRANCH
    ATTN R LIESKE
       R EITMILLER
       F MIRABELLE
    BLDG 120

6   DIR USARL
    ATTN AMSRD ARL WM   B GUIDOS
       M BUNDY   G COOPER
       P WEINACHT
       SIDRA SILTON
       XIAOGAN HUANG
    BLDG 390